

**DFUPG-54-92**

*May 1992*

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Talk presented at the

*VII Scuola Invernale di Fisica Adronica,  
Folgaria (Trento), Italy, February 10–15, 1992*

To be published in the *Proceedings*,  
ed. by T. Bressani, *et al.* (World Scientific, Singapore 1992).

# Low-Energy $KN$ Interactions at a $\phi$ -Factory

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## 1. Introduction.

We intend to illustrate in this lecture the possibilities opening up at machines planned for the nineties for low-energy kaon-nucleon interactions, keeping the focus on the theoretical problems they should help to solve.

We shall deal here only with the  $\phi$ -factory DAΦNE<sup>1</sup> and consider, for brevity, interactions with light, gaseous targets, using gaseous  $H_2$  as a benchmark for which to estimate the rates to be expected in a typical apparatus.

The interest in this field is of a systematic rather than exploratory nature: information on low-energy kaon-nucleon interactions is scarce and of a poor statistical quality, when compared to the corresponding pion-nucleon one. As an example, just take a look at the two pages dedicated by the PDG booklet<sup>2</sup> to  $K^\pm p$  and  $K^\pm d$  total and elastic cross sections: other data do not present a rosier perspective<sup>3</sup>.

The low quality of low-momentum elastic and inelastic scattering data reflects in turn on our knowledge of the “elementary” parameters of the  $KN$  interaction, remarkably poorer than in the  $SU(3)_f$ -related  $\pi N$  case<sup>3</sup>. On top of this sorry situation, one must add the still unsolved mystery of kaonic-hydrogen level-shifts and widths, whose experimental determinations are in total disagreement with theoretical expectations<sup>4</sup>.

Data at very low momenta and at rest are essential to clarify many of the above-mentioned problems<sup>3</sup>; however, experiments of this kind pose formidable problems at conventional fixed-targeted machines, some of which can be circumvented at a  $\phi$ -factory. For instance, at the KAON factory planned for TRIUMF<sup>5</sup>, beams in the lowest momentum range (from 400 to 800  $MeV/c$ ) have intensities of

$10^6 - 10^8 \text{ K}^- \text{s}^{-1}$ , with  $K^+$  beams about twice more intense. Already the purity of these beams is limited by  $K^\pm$  decays in flight: to experiment at momenta below  $400 \text{ MeV}/c$  one has to use moderators, which at the same time decrease the kaon intensity, degrade the beam resolution, and increase enormously the beam contamination at the final target. All these effects make the experiments much more complex, overturning all the advantages offered by the higher initial beam intensities.

## 2. Capabilities of a $KN$ -scattering experiment at DAΦNE.

DAΦNE is the  $\phi$ -factory (the acronym stands for “Double Annular  $\Phi$ -factory for Nice Experiments”), due to replace the Adone colliding-beam machine in the same experimental hall of the I.N.F.N. National Laboratories in Frascati. From its expected commissioning luminosity<sup>6</sup> of  $5 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1}$ , and an annihilation cross section of about  $5 \text{ } \mu\text{b}$  at the  $\phi$ -resonance peak, one can see that its *two* interaction regions will be the sources of  $\simeq 1.2 \times 10^3 \text{ K}^\pm \text{s}^{-1}$ , at a central momentum of  $126.9 \text{ MeV}/c$ , with the momentum resolution of  $\simeq 1.1 \times 10^{-2}$  due to the very small energy spreads in the beams, as well as of  $\simeq 850 \text{ K}_L \text{s}^{-1}$ , at a central momentum of  $110.1 \text{ MeV}/c$ , with the slightly poorer resolution of  $\simeq 1.5 \times 10^{-2}$ .

Both  $\pi^\pm$ 's and leptons coming out of the two sources are easy-to-control backgrounds: the first because the  $\pi^\pm$ 's, though produced at a rate of about  $380 \text{ } \pi^\pm \text{s}^{-1}$  (not counting those from  $K_S$  decays), come *almost all* from events with three or more final particles and can thus be suppressed by momentum and collinearity cuts; the second, as well as collinear pions from  $e^+e^- \rightarrow \pi^+\pi^-$ , produced at much lower rates of order  $0.75 \text{ s}^{-1}$  (the leptons) or  $0.25 \text{ s}^{-1}$  (the pions), are eliminated by a momentum cut, having momenta about four times those of the  $K^\pm$ 's.

The *two* interaction regions are therefore *small-sized* sources of *low-momentum*, *tagged*  $K^\pm$ 's and  $K_L$ 's, with *negligible contaminations* (after suitable cuts on angles and momenta of the particles are applied *event by event*), in an environment of very low background radioactivity: this situation is simply unattainable with *conventional* technologies at fixed-target machines<sup>7</sup>, where the impossibility of placing experiments too close to the production target limits from below the charged-kaon momenta, and kaon decays in flight always contaminate the beams:

low-momentum experiments are thus possible only with the use of moderators, with a huge beam contamination at the target, as well as a large final-momentum spread due to straggling phenomena.

It is therefore of interest to consider the feasibility of low-energy,  $K^\pm N$  and  $K_L N$  experiments at DAΦNE, with respect to equivalent projects at machines such as, e.g., KAON at TRIUMF<sup>8</sup> (or to ideas advanced for the sadly aborted EHF project<sup>9</sup>).

We shall, in this part, try and give an evaluation of rates to be expected in a simple apparatus at DAΦNE. We shall assume cylindrical symmetry, with a toroidal target fiducial volume, limited by radii  $a$  and  $a + d$  and of length  $L$  (inside and outside of which one can imagine a tracking system, surrounded on the outside by a photon detecting system – e.g. lead–Sci–Fi sandwiches – and a superconducting, solenoidal coil to provide the moderate magnetic field  $\mathbf{B}$  needed for momentum measurements), filled with a gas at moderate pressure.

One must convert the usual, fixed-target expression for reaction rates to a spherical geometry, and also include kaon decays in flight, getting (for  $\mathbf{B} = 0$  or  $K_L^0$ 's: the general case can be easily treated with slight modifications)

$$dN_r = \left[ \frac{1}{\rho^2} \left( \frac{3}{8\pi} \right) (L\sigma_\phi B_\phi) \sin^2 \theta e^{-\rho/\lambda} \right] \sigma_r \rho_t (\rho^2 d\rho \sin \theta d\theta d\phi) , \quad (1)$$

with  $\rho$ ,  $\theta$  and  $\phi$  spherical coordinates (with the  $z$ -axis oriented along the beam direction),  $L$  the machine luminosity,  $\sigma_\phi$  the annihilation cross section at the  $\phi$ -resonance peak,  $B_\phi$  the  $\phi$  branching ratio into the desired mode (either  $K^+ K^-$  or  $K_L K_S$ ),  $\sigma_r$  the reaction cross section for the process considered,  $\rho_t$  the target nuclear density, and  $\lambda = p_K \tau_K / m_K$  the decay length (respectively of 0.954  $m$  for  $K^\pm$ 's and of 3.429  $m$  for  $K_L$ 's) at the  $\phi$ -resonance momenta.

Integrating over the fiducial volume, the reaction rate can be cast into the simple formula

$$N_r = \frac{3\pi}{4} r d (L\sigma_\phi B_\phi) \rho_t \sigma_r , \quad (2)$$

with both geometrical acceptance and kaon decay in flight thrown into the reduction factor  $r$ , which we have estimated to take the values 0.50 for  $K^\pm$ 's and 0.72 for  $K_L$ 's for a fiducial volume defined by  $a = 10$  cm,  $d = 50$  cm and  $L = 1$  m, to represent a

“person-sized” detector, fitting in DAΦNE’s interaction region. A longer detector or a larger outer radius would not give any substantial improvement in the rates, due to the angular distribution of the produced kaons and to the value of the decay length  $\lambda$  for these low-momentum  $K$ ’s; besides, for  $K^\pm$   $r$  increases almost linearly but slowly with increasing field  $\mathbf{B}$ , due to the interplay of the increased path length inside the fiducial volume on one side, and of the particle decays on the other.

This gives, for a target volume filled by a diatomic, ideal gas at room temperature, the rates for  $K^\pm$ -initiated processes

$$N_r = p(\text{atm}) \times \sigma_r(\text{mb}) \times (4.0 \times 10^4 \text{ events/y}) , \quad (3)$$

for a “Snowmass year” of  $10^7$  s (for  $K_L$ ’s the figure in eq. (3) is about the same, because of an approximate compensation between the variations in  $r$  and  $B_\phi$ ), or, with rough estimates of the partial  $K^-p$  cross sections at the  $\phi$ -decay momenta, to about  $10^7$  two-body events per year in  $H_2$  gas at atmospheric pressure, of which about  $3.6 \times 10^6$  elastic scattering events,  $2.4 \times 10^6$   $\pi^+\Sigma^-$  and about  $10^6$  for each of the remaining four two-body channels  $\pi^0\Sigma^0$ ,  $\pi^0\Lambda$ ,  $\bar{K}^0n$ , and  $\pi^-\Sigma^+$ . The above rates are enough to measure angular distributions in all channels, and also the polarizations for the self-analyzing final-hyperon states, particularly for the decays  $\Lambda \rightarrow \pi^-p$ ,  $\pi^0n$  (asymmetry  $\alpha \simeq 0.64$ ) and  $\Sigma^+ \rightarrow \pi^0p$  ( $\alpha \simeq -0.98$ ). One could also expect a total of about  $10^4$  radiative-capture events, which should allow a good measurement on the *absolute* rates for these processes as well.

Such an apparatus will need: tracking for incoming and outgoing charged particles, time-of-flight measurements (for charged-particle identification), a moderate magnetic field (due to the low momenta involved) for momentum measurements, and a system of converters plus scintillators for photon detection and subsequent geometrical reconstruction of  $\pi^0$  and  $\Sigma^0$  decays, amounting thus to a rather simple (on today’s particle-physics scale), not too costly apparatus. Mentioning costs, we wish to point out that DAΦNE, though giving the experimenters a very small momentum range, saves them the cost of the *separate* tagging system needed to reject contaminations in a *conventional* low-energy, fixed-target experiment<sup>7</sup>.

The above formulæ for  $K^\pm$  rates do not include particle losses in the beam-pipe wall and in the internal tracking system, which were assumed sufficiently thin

(e. g. of a few hundred  $\mu m$  of low- $Z$  material, such as carbon fibers or Mylar). We have indeed checked that, due to the shape of the angular distribution of the kaons, particle losses are contained (mostly at small angles, where  $K^-$ -production is negligible, and events would anyhow be hard to be fully reconstructed), and momentum losses flat around  $\theta = \pi/2$  (where most of the  $K^\pm$ 's are produced): even for a total thickness of the above-mentioned materials of 1  $mm$ , kaon momenta do not decrease below 100  $MeV/c$  and losses do not grow beyond a few percents. Rather, one could exploit such a thickness as a low-momentum, thin moderator, to span the interesting region just above the charge-exchange threshold at  $p_L(K^-) \simeq 90 MeV/c$ , measurements which would add precious, additional constraints on low-energy amplitude analyses<sup>10</sup>.

We have presented the above simplified estimates to show that acceptable rates can be achieved, orders of magnitude above those of existing data at about the same momentum, i.e. to the lowest-energy points of the British-Polish Track-Sensitive Target (TST) Collaboration, taken in the mid and late seventies at the (R.I.P.) NIMROD accelerator<sup>11</sup>.

Since losses do not affect  $K_L$ 's, a detector of the kind sketched above, similar in geometry to the one proposed by T. Bressani<sup>7</sup> to do  $K^+$ -nucleus scattering and hypernuclear experiments, could be used without any problem to study low-energy  $K_L \rightarrow K_S$  regeneration and charge-exchange in gaseous targets, providing essential information for this kind of phenomena.

We wish to add that a DAΦNE detector dedicated to kaon experiments on gaseous  $H_2$  and  $D_2$  can continue its active life, without substantial changes, to measure  $K^{+-}$ ,  $K^{-}$ , and  $K_L^0$ -interactions on heavier gases as well ( $He$ ,  $N_2$ ,  $O_2$ ,  $Ne$ ,  $Ar$ ,  $Kr$ ,  $Xe$ ), exploring not only the properly nuclear aspects of these interactions, such as nucleon swelling in nuclei<sup>12</sup>, but also producing  $\pi\Sigma$ ,  $\pi\Lambda$  and  $\pi\pi\Lambda$  systems at invariant masses below the elastic  $\bar{K}N$  threshold in the so-called unphysical region, with statistics substantially higher than those now available<sup>13</sup>, due to the  $\simeq 4\pi$  geometry allowed by a colliding-beam-machine detector.

### 3. $KN$ and $\bar{K}N$ amplitudes at low momenta: formalism and some problems.

Any  $a_1(0^-, q) + B_1(\frac{1}{2}^+, p) \rightarrow a_2(0^-, q') + B_2(\frac{1}{2}^+, p')$  process is described in the c.m. frame by two amplitudes  $G(w, \theta)$  and  $H(w, \theta)$ , when the T-matrix element  $T_{\alpha\beta}$  is expressed in terms of two-component Pauli spinors  $\chi_\alpha$  and  $\chi_\beta$  for the final and initial  $\frac{1}{2}^+$  baryon as  $T_{\alpha\beta} = \chi_\alpha^\dagger \mathbf{T} \chi_\beta$ , where

$$\mathbf{T} = G(w, \theta) \times \mathbf{I} + iH(w, \theta) \times (\vec{\sigma} \cdot \hat{n}) \quad (4)$$

and  $\hat{n}$  defines the normal to the scattering plane<sup>14</sup>.

These amplitudes have a simple partial-wave expansion, given by

$$G_N(w, \theta) = \sum_{\ell=0}^{\infty} [(\ell+1)T_{\ell+}(w) + \ell T_{\ell-}(w)] P_\ell(\cos \theta) \quad (5)$$

and

$$H_N(w, \theta) = \sum_{\ell=1}^{\infty} [T_{\ell+}(w) - T_{\ell-}(w)] P'_\ell(\cos \theta) , \quad (6)$$

where the subscript  $N$  indicates that only the nuclear interaction has been considered. To describe the data, they must include electromagnetism and be rewritten as

$$G(w, \theta) = \tilde{G}_N(w, \theta) + G_C(w, \theta) \quad (7)$$

and

$$H(w, \theta) = \tilde{H}_N(w, \theta) + H_C(w, \theta) , \quad (8)$$

where the tilded amplitudes differ from the untilded ones in the Coulomb shifts  $\sigma_{\ell\pm}^{\text{in(fin)}}$ , non-zero only for *both* initial (final) charged particles, having been applied to each partial wave:

$$T_{\ell\pm} \rightarrow \tilde{T}_{\ell\pm} = e^{i\sigma_{\ell\pm}^{\text{in}}} T_{\ell\pm}(w) e^{i\sigma_{\ell\pm}^{\text{fin}}} . \quad (9)$$

The one-photon-exchange amplitudes  $G_C$  and  $H_C$  (absent for charge- or strangeness-exchange processes, but not for  $K_S$  regeneration, which at  $t \neq 0$  goes

also via one-photon exchange) are expressed in terms of the nucleon Dirac form factors as<sup>14,15</sup> ( $\mu$  and  $m$  indicate respectively the meson and baryon masses)

$$G_C(w, \theta) = \pm e^{\pm i\phi_C} \cdot \left\{ \left( \frac{2q\gamma}{t} + \frac{\alpha}{2w} \frac{w+m}{E+m} \right) \cdot F_1(t) + \left[ w - m + \frac{t}{4(E+m)} \right] \cdot \frac{\alpha F_2(t)}{2wm} \right\} \cdot F_K(t) \quad (10)$$

and

$$H_C(w, \theta) = \pm \frac{\alpha F_K(t)}{2w \tan \frac{1}{2}\theta} \cdot \left\{ \frac{w+m}{E+m} \cdot F_1(t) + \left[ w + \frac{t}{4(E+m)} \right] \cdot \frac{F_2(t)}{m} \right\} \quad (11)$$

for  $K^\pm$  interactions with nucleons, while for  $K_S$  regeneration one has to change the sign of the isovector part of the kaon form factor  $F_K(t)$ .

Here  $\gamma = \alpha \cdot (w^2 - m^2 - \mu^2)/2qw$  and the Coulomb phase  $\phi_C$  is defined as

$$\phi_C = -\gamma \log(\sin^2 \frac{1}{2}\theta) + \gamma \cdot \int_{-4q^2}^0 \frac{dt}{t} \cdot [1 - F_K(t)F_1(t)] \quad (12)$$

for charged kaons scattering on protons, while it reduces to

$$\phi_C = -\gamma \int_{-4q^2}^0 \frac{dt}{t} F_K(t)F_1(t) \quad (12')$$

for processes involving  $K^0$ 's and/or neutrons.

$w$  and  $\theta$  are the c.m. total energy and scattering angle,  $q = [\frac{1}{4}w^2 - \frac{1}{2}(m^2 + \mu^2) + (m^2 - \mu^2)^2/4w^2]^{1/2}$  the c.m. momentum (in the initial state: for inelastic processes, including charge exchange, we indicate final-state quantities with primes),  $E$  the c.m. (initial) baryon energy  $E = (w^2 + m^2 - \mu^2)/2w$ , and  $t$  the squared momentum-transfer,  $t = m^2 + m'^2 - 2EE' + 2qq' \cos \theta$ . We shall also use the laboratory-frame, initial-meson momentum  $k = \frac{1}{2}(\omega^2 - \mu^2)^{1/2}$  and energy  $\omega$ , related to the c.m. total energy via  $\omega = (w^2 - m^2 - \mu^2)/2m$ , and, besides  $t$ , the two other Mandelstam variables  $s = w^2$  and  $u$ , the square of the c.m. total energy for the crossed channel  $\bar{a}_2(0^-) + B_1(\frac{1}{2}^+) \rightarrow \bar{a}_1(0^-) + B_2(\frac{1}{2}^+)$ , obeying *on the mass shell* the identity  $s + t + u = m^2 + m'^2 + \mu^2 + \mu'^2$ .

In terms of the amplitudes  $G$  and  $H$  the c.m. differential cross section for an unpolarized target takes the simple form

$$\frac{d\sigma}{d\Omega} = \frac{1}{2} \sum_{\alpha, \beta} |T_{\alpha\beta}|^2 = |G|^2 + |H|^2. \quad (13)$$



The other observable accessible at DAΦNE, in the strangeness-exchange processes  $\bar{K}N \rightarrow \pi\Lambda, \pi\Sigma$ , is the polarization  $P_Y$  ( $Y = \Lambda, \Sigma$ ) of the final hyperon, measurable through the asymmetry  $\alpha$  of their weak, nonleptonic decays  $\Lambda \rightarrow \pi^- p, \pi^0 n$  (both have an asymmetry  $\alpha \simeq 0.64$ ), and  $\Sigma^+ \rightarrow \pi^0 p$  (which has  $\alpha \simeq -0.98$ ), while there is little chance to use the neutron decay modes  $\Sigma^\pm \rightarrow \pi^\pm n$ , which have  $\alpha \simeq \pm 0.068$ ; we have for these quantities

$$P_Y \cdot \left( \frac{d\sigma}{d\Omega} \right) = 2 \operatorname{Im} (G \cdot H^*) . \quad (14)$$

For an  $(S + P)$ -wave parametrization (adequate at such low momenta), while the integrated cross sections depend only quadratically on the  $P$ -waves, both the first Legendre coefficients of the differential cross sections

$$L_1 = \frac{1}{2} \int_{-1}^{+1} \cos \theta \left( \frac{d\sigma}{d\Omega} \right) d \cos \theta = \frac{2}{3} \operatorname{Re} [T_{0+} \cdot (2T_{1+} + T_{1-})^* + \dots] \quad (15)$$

and the polarizations

$$P_Y \cdot \left( \frac{d\sigma}{d\Omega} \right) = 2 \operatorname{Im} [T_{0+} \cdot (T_{1+} - T_{1-})^* + 3T_{1-} \cdot T_{1+}^* \cos \theta + \dots] \sin \theta \quad (16)$$

are essentially linear in the  $P$ -wave contributions, and give complementary information on these latter. It is perhaps not useless to remind that the low-statistics experiments performed only up to the late seventies have been able to put only rather generous upper bounds<sup>11</sup> on these parameters for the hyperon production channels.

We shall devote the last part of this section to show why this absence of *direct* information on the low-energy  $P$ -waves has been a serious shortcoming for  $\bar{K}N$  amplitude analyses. Remember that from *production* experiments we know that the  $I = 1, S = -1$   $T_{1+}$  partial wave resonates *below* threshold at a c.m. energy around  $w = 1385 \text{ MeV}$ , the mass of the isovector member of the  $J^P = \frac{3}{2}^+$  decuplet.

For any analytical extrapolation purpose, one has to turn from the Pauli amplitudes  $G$  and  $H$  to the invariant amplitudes  $A(s, t)$  and  $B(s, t)$ , defined in term of four-component Dirac spinors as

$$2\pi w T_{\alpha\beta} = \bar{u}_\alpha(p') [A(s, t) + B(s, t) \cdot \gamma^\mu Q_\mu] u_\beta(p) , \quad (17)$$

where  $Q = \frac{1}{2}(q + q')$ , the average between incoming- and outgoing-meson c.m. four-momenta: these amplitudes obey simple crossing relations and are free of kinematical singularities, so that they are the ones to be used, rather than  $G$  and  $H$ . It is also customary to use the combination  $D(\nu, t) = A(\nu, t) + \nu \cdot B(\nu, t)$ , where  $\nu = (s - u)/2(mm')^{1/2}$ , which has the same properties as  $A(\nu, t)$  under crossing and for elastic scattering obeys the optical theorem in the simple form

$$\text{Im } D(\nu, t = 0) = k \cdot \sigma_{tot} , \quad (18)$$

where of course all electromagnetic effects must be subtracted on both sides.

$A$  and  $B$  can be rewritten in terms of  $G$  and  $H$  and reexpressed through the partial waves  $T_{\ell\pm}$  by projecting eq. (17) on the different spin states: for elastic scattering one gets

$$A(\nu, t) = \frac{4\pi}{E + m} \{ (w + m)G(w, \theta) + \\ + [(E + m)^2(w - m) + (\frac{1}{2}t + E^2 - m^2)(w + m)] \cdot \frac{H(w, \theta)}{q^2 \sin \theta} \} , \quad (19)$$

and

$$B(\nu, t) = \frac{4\pi}{E + m} \{ G(w, \theta) - [(E + m)^2 - \frac{1}{2}t - E^2 + m^2] \frac{H(w, \theta)}{q^2 \sin \theta} \} . \quad (20)$$

The amplitudes become, leaving out  $D$ - and higher waves,

$$D(\nu, 0) = \frac{4\pi w}{m} [T_{0+} + 2T_{1+} + T_{1-} + \dots] \quad (21)$$

and

$$B(\nu, 0) = \frac{4\pi w}{mq^2} [(E - m)T_{0+} - 2(2m - E)T_{1+} + (E + m)T_{1-} + \dots] . \quad (122)$$

Introducing the (complex) scattering lengths  $a_{\ell\pm}$  and (complex) effective ranges  $r_{\ell\pm}$  one can expand up to  $O(q^2)$ , and obtain for the forward  $D$  amplitudes close to threshold,

$$D(q, 0) = 4\pi(1 + \frac{\mu}{m}) \{ a_{0+} + ia_{0+}^2 q + [2a_{1+} + a_{1-} - (a_{0+} + \frac{1}{2}r_{0+})a_{0+}^2 - \frac{a_{0+}}{2m\mu}]q^2 + \\ + \dots \} , \quad (23)$$

dominated by the  $S$ -waves, while for the  $B$  amplitudes the same approximations give

$$B(q, 0) = \frac{2\pi}{m} \left(1 + \frac{\mu}{m}\right) [a_{0+} - 4m^2(a_{1+} - a_{1-}) + ia_{0+}^2 q + \dots] , \quad (24)$$

where the factor  $4m^2 \simeq 90 \text{ fm}^{-2}$  enhances the low-energy  $P$ -waves (virtually unknown), rendering practically useless the unsubtracted dispersion relation for the better converging  $B$  amplitudes, so important for the  $\pi N$  case in fixing accurately the values of the coupling constant  $f^2$  and of the  $S$ -wave scattering lengths<sup>14</sup>.

#### 4. Impact of DAΦNE on baryon spectroscopy: the states $\Lambda(1405)$ and $\Sigma(1385)$ .

At low momenta, comparable to those of the kaons from DAΦNE, we have data from low-statistics experiments, mostly hydrogen bubble-chamber ones on  $K^-p$  (and  $K^-d$ ) interactions<sup>11,16</sup> (dating from the early sixties through the late seventies), plus scant data from  $K_L$  interactions and  $K_S$  regeneration on hydrogen<sup>17</sup>.

The inelastic channels, open at a laboratory energy  $\omega = \frac{1}{2}M_\phi$  (for  $K^\pm$ 's the value of  $\omega$  at the interaction point has to include ionization energy losses as well), are the two-body ones  $\pi\Lambda$  and  $\pi\Sigma$  (in all possible charge states), plus the three-body one  $\pi\pi\Lambda$  for  $K^-$  or  $K_L$  interacting with nucleons:  $K^+$ -initiated processes are (apart from charge exchange) purely elastic in this energy region.

For interactions in hydrogen, the c.m. energy is limited by momentum conservation to the initial one, equal (neglecting energy losses) to  $w = (m_p^2 + \mu_K^2 + m_p M_\phi)^{1/2}$ , or  $1442.4 \text{ MeV}$  for incident  $K^\pm$ 's and  $1443.8 \text{ MeV}$  for incident  $K_L$ 's. Energy losses for charged kaons can be exploited (using the inner parts of the detector as a moderator) to explore  $K^-p$  interactions in a *limited* momentum range, down to the charge-exchange threshold at  $w = 1437.2 \text{ MeV}$ , corresponding to a  $K^-$  laboratory momentum of about  $90 \text{ MeV}/c$ .

For interactions in nuclei, momentum can be carried away by spectator nucleons, and the inelastic channels can be explored down to threshold. The possibility of reaching energies below the  $\bar{K}N$  threshold allows exploration of the unphysical region, containing two resonances, the  $I = 0$ ,  $S$ -wave  $\Lambda(1405)$  and the  $I = 1$ ,  $J^P = \frac{3}{2}^+$   $P$ -wave  $\Sigma(1385)$ , observed mostly in production experiments (and, in the first case, in very limited statistics ones<sup>13</sup>): the information on their couplings

to the  $\bar{K}N$  channel relies entirely on extrapolations of the low-energy  $\bar{K}N$  data. The coupling of the  $\Sigma(1385)$  to the  $\bar{K}N$  channel, for instance, can be determined via forward dispersion relations involving the total sum of data collected at  $t \simeq 0$ , but still with uncertainties which are, *at their best*, still of the order of 50% of the flavour- $SU(3)$  symmetry prediction<sup>18</sup>; as for the  $\Lambda(1405)$ , even its spectroscopic classification is an open problem, *vis-à-vis* the paucity and (lack of) quality of the best available data<sup>19</sup>.

A formation experiment on *bound* nucleons, in an (almost)  $4\pi$  apparatus with good efficiency and resolution for low-momentum  $\gamma$ 's (such as KLOE<sup>20</sup>), can measure a channel such as  $K^-p \rightarrow \pi^0\Sigma^0$  (above threshold), or  $K^-d \rightarrow \pi^0\Sigma^0 n_s$  (both above and below threshold), which is pure  $I = 0$ : up to now all analyses on the  $\Lambda(1405)$  have been limited to charged channels<sup>13</sup>, and assumed the  $I = 1$  contamination to be either negligible or smooth and non-interfering with the resonance signal. Since the models proposed for the  $\Lambda(1405)$  differ mostly in the details of the resonance shape, rather than in its couplings, and it is precisely the shape which could be changed even by a moderate interference with an  $I = 1$  background, such measurements would be decisive. Having in the same apparatus and at almost the same energy *tagged*  $K^-$  and  $K_L$  produced at the same point, one can further separate  $I = 0$  and  $I = 1$  channels with a minimum of systematic uncertainties, by measuring all channels  $K_L p \rightarrow \pi^0\Sigma^+$ ,  $\pi^+\Sigma^0$  and  $K^-p \rightarrow \pi^-\Sigma^+$ ,  $\pi^+\Sigma^-$ , besides, of course, the above-mentioned, pure  $I = 0$ ,  $K^-p \rightarrow \pi^0\Sigma^0$  one.

Another class of inelastic processes which are expected to be produced, at a much smaller rate, by DAΦNE's kaons are the radiative capture processes  $K^-p \rightarrow \gamma\Lambda$ ,  $\gamma\Sigma^0$  and  $K_L p \rightarrow \gamma\Sigma^+$  (both in hydrogen and deuterium), and  $K^-n \rightarrow \gamma\Sigma^-$  and  $K_L n \rightarrow \gamma\Lambda$ ,  $\gamma\Sigma^0$  (only in deuterium). Up to now only searches for photons emitted after stops of  $K^-$ 's in liquid hydrogen and deuterium have been performed with some success: the spectra are dominated by photons from unreconstructed  $\pi^0$  and  $\Sigma^0$  decays<sup>21</sup>, and separating the signals from this background poses serious difficulties, since only the photon line from the  $\gamma\Lambda$  final state falls just above the endpoint of the photons from  $\pi^0$  decays in the  $\pi^0\Lambda$  final state, while that from  $\gamma\Sigma^0$  falls right on top of the latter. Indeed these experiments were able to produce only an estimate of the respective branching ratios<sup>21</sup>.

The  $4\pi$  geometry possible at DAΦNE, combined with the “transparency” of a KLOE-like apparatus<sup>20</sup>, its high efficiency for photon detection and its good resolution for spatial reconstruction of the events, should make possible the full identification of the final states and therefore the measurement of the absolute cross sections for these processes, although in flight and not at rest.

Data<sup>21</sup> are presently indicating branching ratios around  $0.9 \times 10^{-3}$  for  $K^- p \rightarrow \gamma\Lambda$  and  $1.4 \times 10^{-3}$  for  $K^- p \rightarrow \gamma\Sigma^0$ , with errors of the order of 15% on both: most models<sup>23</sup> give the first rate larger than the second, with both values consistently higher than the observed ones. Only a cloudy-bag-model<sup>24</sup> exhibits the trend appearing (although only at a  $2\sigma$ -level, and therefore waiting for confirmation by better data) from the first experimental determinations, but this is the only respect in which it agrees with the data, still giving branching ratios larger than observations by a factor two.

Data are also interpretable in terms of  $\Lambda(1405)$  electromagnetic transition moments<sup>22</sup>: this interpretation is clearly sensitive to the interference between the decay of this state and all other contributions. An extraction of the  $\Lambda(1405)$  moments free of these uncertainties would require measurements of  $\gamma\Lambda$  and  $\gamma\Sigma$  (if possible, in different charge states) over the unphysical region, using (gaseous) deuterium or helium as a target. Rates are expected to be of the order of  $10^4$  *events/y* only, but such a low rate would correspond to better statistics than those of the best experiment performed on the  $\Lambda(1405) \rightarrow \pi\Sigma$  decay spectrum<sup>13</sup>.

## 5. Description of coupled $\bar{K}N$ , $\pi Y$ channels: the K-matrix.

A description of the low-energy  $\bar{K}N$  partial waves must couple the two-body inelastic channels to each other and to the elastic one: the three-body channel  $\pi\pi\Lambda$  is expected to be suppressed, for  $J^P = \frac{1}{2}^-$ , by the angular momentum barrier, but it could contribute appreciably to the  $I = 0$ ,  $J^P = \frac{1}{2}^+$   $P$ -wave, due to the strong final-state interaction of two pions in an  $I = 0$   $S$ -wave. Most bubble-chamber experiments were unable to fully reconstruct events at the lowest momenta, and therefore assumed all *directly* produced  $\Lambda$ 's to come from the  $\pi\Lambda$  channel alone, neglecting the small  $\pi\pi\Lambda$  contribution altogether.

The appropriate formalism is to introduce a K-matrix description (sometimes

it is convenient to use, instead of the K-matrix, its inverse, *a.k.a.* the M-matrix), defined in the isospin eigenchannel notation as

$$\mathbf{K}_{\ell\pm}^{-1} = \mathbf{M}_{\ell\pm} = \mathbf{T}_{\ell\pm}^{-1} + i \mathbf{Q}^{2\ell+1} , \quad (25)$$

for both  $I = 0, 1$   $S$ -waves (and perhaps also for the four  $P$ -waves as well). The K-matrices, assuming  $SU(2)$  symmetry, describe the  $S$ -wave data at a given energy in terms of *nine* real parameters (six for  $I = 1$  and three for  $I = 0$ ), while the experimentally accessible processes are described, with pure  $S$ -waves and in the same symmetry limit, by only *six independent* parameters, for which one can choose the two (complex) amplitudes  $A_{0,1}$  for the elastic channel, the phase difference  $\phi$  between the  $I = 0$  and  $I = 1$   $\pi\Sigma$  production amplitudes, and the ratio  $\epsilon$  between the  $\pi\Lambda$  production cross section and that for total hyperon production in an  $I = 1$  state<sup>25</sup>.

Thus a single-energy measurement does not allow a complete determination of the K-matrix elements. For a precise determination of the  $S$ -waves one should also subtract out the  $P$ -wave contributions to the integrated cross sections

$$\sigma = 4\pi L_0 = 2\pi \int_{-1}^{+1} \left( \frac{d\sigma}{d\Omega} \right) d\cos\theta = 4\pi[|T_{0+}|^2 + 2|T_{1+}|^2 + |T_{1-}|^2 + \dots] , \quad (26)$$

which could be obtained either from  $L_1$  alone for the elastic and charge-exchange channels, or from both  $L_1$  and  $P_Y$  for the hyperon production channels. None of these quantities has been measured up to now: the TST Collaboration tried to extract  $L_1$  from some of their low-statistics data, but found results consistent with zero within their obviously very large errors<sup>11</sup>. At the same level of accuracy, one should also be able to isolate out the  $\pi\pi\Lambda$  channel as well. Note that an accurate analysis has also to include complete e.m. corrections<sup>15,26</sup>: up to now all  $\bar{K}N$  analyses have relied on the old, approximate formulæ derived by Dalitz and Tuan for a pure  $S$ -wave scattering<sup>27</sup>.

To fix the redundant K-matrix parameters different ways have been tried: some authors have used the data on the shape of the  $\pi\Sigma$  spectrum from production experiments<sup>28</sup>, others have constrained the amplitudes in the unphysical region by imposing consistency with forward dispersion relations for both  $K^\pm p$  and  $K^\pm n$

elastic-scattering  $D$  amplitudes<sup>29</sup>, relying on the accurate total-cross-section data at higher energies. More recently, some attempts have been made to combine both constraints into a global analysis, but with no better results than each of them taken separately<sup>30</sup>.

Unfortunately, neither of these methods has been very powerful because of the low statistics of the  $\pi\Sigma$ -production data on one side, and on the other because of the need to use for the dispersion relations the often inaccurate information (and particularly so for the  $K^\pm n$  amplitudes) on the real-to-imaginary-part ratios.

We list below the constant  $K$ -matrices found by Chao *et al.* using the first method<sup>28</sup>, which did not include the TST Collaboration data, and the more complex parametrization found by A.D. Martin using the second<sup>29</sup>, and including the preliminary TST data. Note that to describe the data for  $I = 0$  both above and below threshold A.D. Martin had to introduce a constant-effective-range  $M$ -matrix  $\mathbf{M}^{(0)} = (\mathbf{K}^{(0)})^{-1} = \mathbf{A} + \mathbf{R}k^2$ , so that to make the two analyses comparable we list separately his threshold  $K$ -matrix values.

**Table I**

<i>Chao et al.</i>	<i>A. D. Martin</i>
$K_{NN}^{(0)} = -1.56 fm$ $A_{NN} = -0.07 fm^{-1}$ $R_{NN} = +0.18 fm$ $K_{NN}^{(0)}(0) = -1.65 fm$ $K_{N\Sigma}^{(0)} = -0.92 fm$ $A_{N\Sigma} = -1.02 fm^{-1}$ $R_{N\Sigma} = +0.19 fm$ $K_{N\Sigma}^{(0)}(0) = +0.16 fm$ $K_{\Sigma\Sigma}^{(0)} = +0.07 fm$ $A_{\Sigma\Sigma} = +1.94 fm^{-1}$ $R_{\Sigma\Sigma} = -1.09 fm$ $K_{\Sigma\Sigma}^{(0)}(0) = -0.15 fm$	
$K_{NN}^{(1)} = +0.76 fm$	$K_{NN}^{(1)} = +1.07 fm$
$K_{N\Sigma}^{(1)} = -0.97 fm$	$K_{N\Sigma}^{(1)} = -1.32 fm$
$K_{N\Lambda}^{(1)} = -0.66 fm$	$K_{N\Lambda}^{(1)} = -0.30 fm$
$K_{\Sigma\Sigma}^{(1)} = +0.86 fm$	$K_{\Sigma\Sigma}^{(1)} = +0.27 fm$
$K_{\Sigma\Lambda}^{(1)} = +0.51 fm$	$K_{\Sigma\Lambda}^{(1)} = +1.54 fm$
$K_{\Lambda\Lambda}^{(1)} = +0.04 fm$	$K_{\Lambda\Lambda}^{(1)} = -1.02 fm$

The table shows that there is considerable uncertainty even on the  $K_{NN}^{(I)}$  elements (the real parts of the corresponding scattering lengths): the data have been

re-analyzed by Dalitz *et al.*<sup>30</sup>, using both sets of constraints with different weights and different parametrizations, and yielding a variety of fits, all of them of about the same quality of, but none of them improving very much over, the above ones.

To further highlight the difficulties met in fitting the data, we point out that A.D. Martin himself<sup>29</sup> found that including in his analysis a  $\Sigma(1385)$  resonance with the width given by production experiments and the coupling to the  $\bar{K}N$  channel dictated by flavour- $SU(3)$  symmetry, was worsening rather than improving the results obtained neglecting it altogether. He proposes therefore to consider the  $\Sigma$  Born-term contribution a superposition of the former and of that of the  $P$ -wave resonance: a rather unsavoury situation, considering the different  $J^P$  of the two states, which may raise questions about the applicability of his analysis away from  $t \simeq 0$ . An analogous superposition is considered in  $K^\pm p$  dispersion relations, where one can not separate the  $\Sigma$ - from the  $\Lambda$ -pole, but here the two contribute to the same partial wave, and the  $\Sigma$ -pole can be extracted independently from data on  $K^\pm n$  scattering and  $K_S$  regeneration on protons<sup>31,32</sup>.

In the analysis of the low-energy data collected in the past, a further difficulty comes from the large momentum spread of the low-energy kaon beams, for  $K^\pm$ 's because of the degrading in a moderator of the higher-energy beams needed to transport the kaons away from their production targets, for  $K_L$ 's because of the large apertures needed to achieve satisfactory rates in the targets (typically bubble chambers): this made unrealistic the proposals (advanced from the early seventies) of better determining the low-energy  $K$ -matrices by studying the behaviour of the cross sections for  $K^-p$ -initiated processes at the  $\bar{K}^0 n$  charge-exchange threshold<sup>10</sup>. The high momentum resolution available at DAΦNE will instead make such a goal a realistically achievable one.

In this case  $SU(2)$  can no longer be assumed to be a symmetry of the amplitudes: under the (reasonable) assumption that the forces are still  $SU(2)$ -symmetric, one can however retain the previous  $K$ -matrix formalism, but no longer decouple the different isospin eigenchannels<sup>33</sup>. Introducing the orthogonal matrix  $\mathbf{R}$ , which transforms the six isospin eigenchannels for  $\bar{K}N$  ( $I = 0, 1$ ),  $\pi\Lambda$  ( $I = 1$  only) and  $\pi\Sigma$  ( $I = 0, 1, 2$ ) into the six charge-states  $K^-p$ ,  $\bar{K}^0 n$ ,  $\pi^0\Lambda$ ,  $\pi^-\Sigma^+$ ,  $\pi^0\Sigma^0$  and  $\pi^+\Sigma^-$ , and the diagonal matrix  $\mathbf{Q}_c$  of the c.m. momenta for these latter, one can rewrite



the T-matrix in the isospin-eigenchannel space for the  $S$ -waves as

$$\mathbf{T}_I^{-1} = \mathbf{K}_I^{-1} - i\mathbf{R}^{-1}\mathbf{Q}_c\mathbf{R} , \quad (27)$$

where  $\mathbf{K}_I$  is a box matrix with zero elements between channels of different isospin, and  $\mathbf{R}^{-1}\mathbf{Q}_c\mathbf{R}$  is of course no longer diagonal.

Apparently this involves one more parameter, since it also contains the element  $K_{\Sigma\Sigma}^{(2)}$ : in practice, if one is interested in the cross sections only in the neighbourhood of the  $\bar{K}N$  charge-exchange threshold, one can take the c.m. momenta in the three  $\pi\Sigma$  channels as equal and decouple the  $I = 2$ ,  $\pi\Sigma$  channel from the  $I = 0, 1$  ones, since the “rotated” matrix  $\mathbf{R}^{-1}\mathbf{Q}_c\mathbf{R}$  has now only two non-zero, off-diagonal elements, equal to  $\frac{1}{2}(q_0 - q_-)$  (the subscripts refer to the kaon charges), between the  $I = 0$  and  $I = 1$   $\bar{K}N$  channels, the diagonal ones being the same as in the  $SU(2)$ -symmetric case, if one substitutes for the  $\bar{K}N$  channel momentum  $q$  the average over the two charge states  $\frac{1}{2}(q_0 + q_-)$ . Indeed  $K_{\Sigma\Sigma}^{(2)}$  could only be important for an accurate description of the  $\pi\Sigma$  and  $\pi\Lambda$  mass spectra close to the  $\pi\Sigma$  threshold.

## 6. Outline of a theoretical program for a modern $KN$ amplitude analysis.

The measurements proposed for DAΦNE will provide data of the same statistical quality now available *only* for the  $\pi N$  system: theoretical tools for their analysis must thus be improved as well, to meet the standards required by this, long awaited for, “forward leap” in  $KN$  data. Since long, tools of just this level have been provided, for  $\pi N$  amplitude analysis, by the so-called “Karlsruhe-Helsinki collaboration” headed over the years by Prof. G. Höhler<sup>14,34</sup>: alas, their software can not be straightforwardly imported to do  $KN$  analyses, mainly because of the complicated analytic structure of the low-energy  $\bar{K}N$  amplitudes.

Much for the same reason, the dispersive treatment of Coulomb corrections, developed at NORDITA<sup>15,26</sup> by Hamilton and collaborators, can not be immediately transferred to the strange sector. It has to be recalled that old data were always analyzed using, for these corrections, the approximate formula of Dalitz and Tuan<sup>27</sup>, which considers only a pure- $S$ -wave strong interaction, and furthermore might be inapplicable to a *strongly absorptive* interaction close to threshold<sup>35</sup>.

Since the basic principles, on which both approaches are based, have to hold for the  $\bar{K}N$  system as for the  $\pi N$  one, it remains only to work out the details of a partial-wave-analysis procedure, applicable to a system strongly absorptive at threshold, and possessing *ab-initio* the following requirements: i) consistency with both fixed- $t$  and partial-wave dispersion relations; ii) crossing symmetry (and isotopic-spin symmetry as well, to describe *simultaneously* charge-exchange and regeneration data); iii) analyticity in  $t$  beyond the Lehman ellipses, with the *correct* low-mass,  $t$ -channel-cut discontinuities given by the  $\pi\pi$  cut; iv) a *complete* treatment of radiative and Coulomb corrections.

The author and its collaborators (chiefly G. Violini of Università della Calabria, Cosenza, and C.I.F., Bogotá, and R.C. Barrett of the University of Surrey, Guildford) have in the past carried out parts of this program (as many others have done, more or less at the same epoch), but only for *limited purposes*, such as extrapolations either to the hyperon poles<sup>31,36</sup> or to the Cheng-Dashen point<sup>37</sup>, or studies of Coulomb effects<sup>35</sup> and radiative capture at threshold<sup>24</sup>: what remains to be done is a merging together of all these techniques into a “global” analysis, on which work is presently under way.

In this perspective we have advanced the proposal to I.N.F.N. for a program of extensive collaboration, code-named KILN (for “Kaon Interactions at Low energies with Nucleons”), which has already received an initial, and thus limited, financial support. Participation in this collaboration is highly welcome, and we take this occasion for calling upon all theorists wick have been or wish to be active in this still open and very much alive (despite greatly exaggerated rumors on the contrary<sup>38</sup>) field of particle physics.

## ACKNOWLEDGEMENTS

Exchanges of information with theorists and experimentalists involved in the planning of experiments at both machines, KAON and DAΦNE, is gratefully acknowledged by the author and his collaborators.

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38. The same also happened to Mark Twain, from which we took the liberty of borrowing the pun.